Add the following new claim:

-- 36. -- (new) The sensor system according to claim 18 wherein said mean for variable control of exposure time operates to produce successive image frames of respective long and short duration, the light from the stars being produced on long duration image frames and the light from the earth being produced on the short duration frames.

In the Abstract

Attached hereto is a copy of the Abstract as filed.

REMARKS

Careful consideration has been given to the Official Action of September 12, 2002 and reconsideration of the application as amended is respectfully requested.

The Examiner has raised objection to the drawing on the grounds that it fails to include reference numeral 8 as recited on page 6 of the specification, namely "window 8". We have not found this expression in the specification and it would be appreciated if the Examiner would point this out specifically so that appropriate amendatory action can be taken. The windows which allow the light passage from the stars and from the earth are designated in the drawing by windows 6 and 7. If as stated by the Examiner that numeral 8 is employed in the specification to designate one of the aforesaid windows this is in error and appropriate amendatory action will be taken in the specification as noted by the Examiner, numeral 8 is shown in Figure 2 as directed to a beam splitter.

The Examiner objects to the specification as not containing an abstract of the disclosure. This is not understood as the specification was originally filed with an abstract and a copy thereof has been appended hereto.

In respect of the objection raised by the Examiner concerning the recitation of "a space vehicle" in lines 2 and 9, amendatory action has been taken to clearly establish that applicant is referring to the same space vehicle as so interpreted by the Examiner.

The Examiner has rejected claims 25-30 and these claims have been cancelled without prejudice thereby obviating the rejection raised by the Examiner.

Claims 33 and 34 have been rejected under 35 USC 112 on the grounds that there is not adequate description in the specification to make and/or use the invention. The rejection is respectfully traversed as the specification contains an enabling disclosure, for example on page 4, at paragraph 3 wherein it is recited "e.g. by means of edge filters" in order to filter out a long wave fraction of radiation and on page 8, last paragraph, where it is recited "an orbit-dependent model of the earth and of the earth's atmosphere ..." to show how the model based tracking is carried out. It is respectfully submitted that there is adequate disclosure of the subject matter of claims 33 and 34 to enable those skilled in the art to practice the invention.

Claim 18, has been rejected under 35 USC 112 because the Examiner finds unclear the "means for variable control of exposure time". The Examiner contends that there is no structure or circuit mentioned in the specification that correspond to the aforesaid means". This quote means is supported in the specification by the description on page 3, second and fifth paragraphs as well as paragraph 4 on page 7 from which it is clear that the image pickup devices 4 include the "means for variable control of exposure time ..." and that the control of the exposure time is effected by choosing alternate long and short integration times of the image pickup devices. Claim 36 has been added as directed to this feature and as supported by the aforesaid description in the specification.

The Examiner has rejected claims 18-24 under 35 USC 103 as being unpatentable over Falbel in view of Frame . Claims 31-35 have been rejected under the same combination with the addition of Billing-Ross.

The rejection of the claims under 35 USC 103 cannot be sustained because the Frame patent is not available to the Examiner as a reference. Namely the Frame patent has a United States filing date of August 25, 1999 whereas the present application has a priority date of October 9, 1998 based on the German priority application. The PCT application which was filed on the basis of the German priority application contains a translation of the German application. The instant application is a national phase entry of the PCT application. The certified copy of the German application has been filed and a verified translation of accuracy thereof is attached hereto.

Accordingly applicant's priority of his German application predates the filing date of the Frame patent thereby disqualifying this as a reference under 35 USC 102 or 35 USC 103 and thereby the rejection on cited art, therefore, falls. It is also noted that the formal Falbel patent, cited by the Examiner as the primary reference, discloses in Column 4, lines 9-12, the use of an integration time of 1/3 of a second and thus a fixed integration time in contrast to

the different exposure time or integration time depending on the image brightness of the stars and the earth observations. It is respectfully submitted that the application is now in allowable condition, early notice of which would be appreciated.

On the basis of the above action and comments.

Respectfully submitted,

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IN THE SPECIFICATION

It is also possible to compensate for the difference in brightness of stars compared to that of the earth, by suitable control of the exposure time or the integration time of the image pickup devices 4. To this effect, during operation, exposure is always in turn, one frame long and one frame short. In the respective frame that has a relatively long exposure time, e.g. 0.1 sec., the stars are optimally acquired while in the subsequent frame with relatively short exposure time, e.g. 0.0001 sec., the rim of the earth is acquired particularly accurately.

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CLAIMS

Claim 18 (amended) A combined earth-star sensor system for three-axis attitude determination of a satellite in space, said combined earth-star sensor system (1) comprising separate apertures with different directions of observation of earth and stars <u>to receive light from the earth and stars, having respective levels of brightness</u> and common image pickup devices (4) for the earth observation and the star observation [and] <u>including</u> means for variable control of exposure time of earth and star observations <u>by said common image pickup devices</u> depending on <u>the</u> brightness of the earth and the stars being observed.

Claim 20 (amended) The sensor system according to claim [19] <u>18</u>, comprising an optical arrangement (9) for star observation, an optical arrangement (10) for earth observation and a semitranslucent beam splitter (8) between said apertures and the optical arrangements for deviating laterally entering light from the earth and transmitting light from the observed star, to the image pickup devices (4).

Claim 31 (Amended) A method for simultaneous orbit determination and attitude determination of a space vehicle, comprising:

simultaneously forming images of a star and the rim of the earth in one focal plane of a sensor system;

determining attitude of the star in said focal plane;

determining the rim of the earth by image processing;

determining rates of rotation of the sensor system from movement of the star image in the focal plane; and

calculating at least one of orbit and altitude of [a] <u>the</u> space vehicle carrying the sensor system, wherein

exposure or integration time of the sensor system is alternatingly adapted to a difference in brightness of the light from the star and the earth.

Claim 34 (amended) The method according to claim 31, comprising filtering a long-wave fraction of the [radiation] <u>light</u> used for determining the rim of the earth.

CERTIFICATION OF TRANSLATION

"PCT/DE99/03204"

I, Roland Meier, c/o Technisches Fachübersetzungsbüro, Försterweg 33, A-2136 Laa/Thaya, Austria, am the translator of the documents attached and certify that the following is an accurate and literal translation to the best of my knowledge and belief.

R Meier

Signature of translator   dated this 1st day of March 2001

A combined earth-star sensor system and a method for determining the orbit and attitude of space vehicles

The invention relates to a combined earth-star sensor system for three-axis attitude determination of satellites in space, as well as a method for determining the orbit and attitude of space vehicles.

For earth-oriented satellites, infrared sensors are presently used to determine roll and pitch angles, while solar sensors are used to determine the yaw angle of the satellite. This solution is associated with the disadvantage of the arrangement of several solar sensor heads used being very expensive, and of the lack of any yaw reference in the case of co-linearity of the earth and the sun. Furthermore, evaluation additionally requires an exact knowledge of the attitude of the satellite on its orbit. Moreover, errors between the measuring axes of solar sensors and earth sensors, e.g. caused by inaccuracies during installation or as a result of thermal influence, can significantly degrade the quality of measurements.

Known star sensors provide a three-axis attitude reference in an inertial system. Here too, earth alignment requires an exact knowledge of the satellite attitude. At present, CCDs are used for such star sensors. Due to their lack of radiation resistance, they are not suitable for use in orbits with substantial radiation load, e.g. for use in geosynchronous missions.

From EP 0 589 387 A1 a combined earth-star sensor system is known which uses a single optical arrangement to carry out both star observation and earth observation in the UV range. To carry out common observation, the optical arrangement comprises a wide-

angle system incorporating a mirror system. Due to the coinciding directions of observation for earth observation and star observation, the known system is only able to observe stars in proximity to the earth; and due to the sensor being designed with the strong earth radiation in mind, for attitude determination the known system is only able to observe stars of high intensity.

It is thus the object of the invention to provide a combined earth-star sensor system which is not limited in regard to the selection of stars suitable for observation, and which can be produced economically. Furthermore, it is the object of the invention to provide a method for determining the orbit and attitude of a space vehicle, said method being more accurate and allowing independent on-board operation.

This object is met by the combined earth-star sensor system according to claim 1 and the method according to claim 5. Further advantageous characteristics, aspects and details of the invention are provided in the dependent claims, the description and the drawings.

The combined earth-star sensor system according to the invention, for three-axis attitude determination of satellites in space comprises separate apertures with different directions of observation and common image pickup devices for the earth sensor and the star sensor.

Observation according to the invention, of the earth and the stars with different apertures makes it possible to observe stars of magnitude 5 too. The considerable difference in the intensity of radiation of these stars when compared to earth radiation, can be absorbed by different aperture design and filtering. In

spite of concurrent observation of the earth, the detection of the stars is not influenced by the scattered light from the earth, if two apertures are used. The simple design of the system according to the invention can cope with high light intensities while keeping costs low. High light intensity allows the use of economical CMOS image pickup devices.

Preferably the CMOS image pickup devices form a CMOS focal plane array as a focal plane sensor with a dynamic range of up to $1:10^6$. It makes possible variable control of the exposure time, so that integration can be adapted to the difference in brightness of the stars and the earth.

By using an alternative proposal of two different optical arrangements instead of a common optical arrangement, the wavelength bands used for detection can be optimised independently of each other.

The integrated sensor system according to the invention makes it possible to determine three attitude angles, three angle speeds, and the attitude of the space vehicle. Software control makes it possible to cover different orbits such as geosynchronous orbits, transfer orbits as well as low, middle and elliptical orbits.

Furthermore, the sensor makes possible variable control of the exposure time so that integration can be adapted to the difference in brightness of the stars and the earth. Preferably, exposure is always in turn, one frame long and one frame short.

The method according to the invention comprises the following steps:

simultaneous imaging of stars and rim of the earth in one focal plane of a sensor system; determining the star attitude in the focal plane; determining the rim of the earth by image processing; determining rates of rotation of the sensor system from the movement of the star image in the focal plane; and calculating the orbit and/or attitude of a space vehicle which carries the sensor system.

With the device and the method, highly accurate information on the orbit and the attitude of the space vehicle or satellite can be obtained concurrently.

By alternate adaptation of the exposure time or the integration time of the sensor or of the image pickup device, to the brightness of the stars and the brightness of the earth, even stars which are less bright can be acquired concurrently with the rim of the earth. By filtering out or acquiring a long-wave fraction of the radiation, e.g. by means of edge filters, the rim of the earth can be acquired particularly well and with particularly good stability. Additional degrees of freedom can be determined by model-based tracking of the rim of the earth.

Further advantages of the invention include a lower mass or possible redundancy because there is no need for further equipment such as for example gyros which were hitherto required for determining the orbit and the attitude. This results in simplified integration and inherent radiation resistance. Orbit determination is possible without the use of GPS, in particular also for near earth and geostationary satellites. In this way, independent on-board operation can be achieved.

Below, embodiments of the invention are explained in more detail by means of the drawing.

Figure 1 shows a combined earth-star sensor system with a common optical arrangement;

Figure 2 shows a combined earth-star sensor system with two optical arrangements;

Figure 3 shows an arrangement of image pickup devices; and

Figure 4 shows a coordinate system whose Z-axis is directed towards the centre of the earth and whose X-axis points in the direction of orbit movement.

The combined earth-star sensor system 1 shown in Figure 1 comprises a common optical arrangement 2, a deflection mirror 3, image pickup devices 4 and windows 6 and 7 for earth and star observation.

The system shown is in particular characterised in that the observation direction to the earth differs from the observation direction to the stars.

Starlight enters the window 6, passes the little deflection mirror 3, reaches the common optical arrangement 2 and is focussed onto the image pickup device 4. The light from the earth enters through the window 7, impinges on the deflection mirror 3 which directs it to the common optical arrangement 2. The common optical arrangement 2 focuses the light from the earth on the image pickup devices 4. In relation to a common optical arrangement 2, the image pickup devices 4 are arranged on a common focal plane according to a specified pattern. Figure 3 provides an example of a possible arrangement of four image pickup devices which provide coverage over a large field of vision at a

minimum number of pixels. For example, known CCD components can be used as image pickup devices, but other components such as e.g. CMOS image pickup devic e can also be used.

The aperture for earth observation is a small aperture which during observation of fainter stars preferably avoids interfering scattered light from the earth, and attenuates intensive sunlight which occurs at times when the sun appears in the beam path to the earth. The image ot the earth through window 7 and the images of the stars through window 8 are superimposed on the image pickup devices.

The evaluation system of the combined earth-star sensor cystem 1 achieves the ooparation of oarth imago from star image e.g. in the following way: the rim of the earth is roughly determined in the image, i.e. determination is not to subpixel accuracy, then the image of the stars which are clearly attitudeed outside the earth's disk are evaluated; to this effect the stars are compared with the star chart; in the star chart, those stars are determined whose image is too close to the rim of the earth, e.g. up to 3 pixels, and which would thus disturb an exact location determination; the rim of the earth is then located to subpixel accuracy, with those pixels not being counted which are too close to disturbing stars.

It the ditterence in apertures is sufficient, then the stars which can be observed through the earth aperture do not interfere; their light is attenuated too much by the smaller aperture. Sun and moon however have to be taken into account, but on account of their large surface area they can easily be differentiated from stars.

As an alternative to the system with a common optical arrangement, Figure 2 shows a system with separate optical arrangements for observing the earth and the stars. In this case the combined earth-star sensor system 1 comprises a semitranslucent beam splitter 8, an optical arrangement 9 for star observation, an optical arrangement 10 if necessary with a deflection mirror 11 for earth observation arranged upstream of said optical arrangement, as well as windows 6 and 7 and image pickup devices 4.

The optical arrangement 10 for earth observation is directly inserted in window 7. Via the semitranslucent beam splitter 8, said optical arrangement forms an image on the image pickup devices 4, of the earth radiation received, if necessary via an outer deflection mirror 11. Via the beam splitter 8, the optical arrangement 9 forms an image on the image pickup devices 4, of the starlight received through window 6. Figure 2 shows the image pickup devices 4 in a common focal plane to the beam splitter 8. The optical characteristics of the two sensors can be such that they compensate for differences in intensity; they can also be of different focal length and comprise additional attenuation filters in the beam path.

As is the case in the system described in the context of Figure 1, the aperture for earth observation is attenuated and smaller than the aperture for star observation, and the observation direction to the earth differs from the observation direction to the stars.

It is also possible to compensate for the difference in brightness of stars compared to that of the earth, by suitable control of the exposure time or the integration time. To this effect, during operation, exposure is always in turn, one frame long and one

frame short. In the respective frame that has a relatively long exposure time, e.g. 0.1 sec., the stars are optimally acquired while in the subsequent frame with relatively short exposure time, e.g. 0.0001 sec., the rim of the earth is acquired particularly accurately.

First the star attitude is determined in the image plane. Then, by tracking the acquired stars, the movements $(\frac{dx}{dt}, \frac{dy}{dt})$ of the stars in the image plane are obtained. Subsequently, the rates of rotation $(\omega_x, \omega_y, \omega_z)$ are determined by solving the following equations:

$$\frac{dx}{dt} = \frac{xy}{f}\omega_x + \left(-f - \frac{x^2}{f}\right)\omega_y + y\omega_z$$

$$\frac{dy}{dt} = \left(f + \frac{y^2}{f}\right)\omega_x - \frac{xy}{f}\omega_y - x\omega_z \qquad (1)$$

with f denoting the focal length of the optical arrangement. The degrees of freedom of rotation of the space vehicle can be determined by tracking at least 2 stars (x_i, y_i) in the image plane.

To explain the equations, Figure 4 shows the image plane x, y and a system of coordinates, with the satellite travelling in the X direction and with the Z-axis pointing to the centre of the earth. The rates of rotation $\omega_x, \omega_y, \omega_z$, reflect the roll, the pitch and yaw of the satellite or space vehicle.

In the next step the rim of the earth is determined to subpixel accuracy, after respective segmentation. For this purpose, an orbit-dependent model of the earth and of the earth's atmosphere is fitted to the intensity distribution in the image plane. It must be taken into

account that the image has already been defocused (via 2 - 3 pixels) for star attitude determination at subpixel accuracy. For determination to subpixel accuracy there is an interpolation between the individual pixel values. Segmentation, i.e. separation of the image according to earth and star, results in improved accuracy.

If the earth is imaged in its entirety or as a sufficiently curved segment of a circle, the vector to the centre of the earth can be estimated.

Now the following formula is used to determine the orbital movement $(v_x, v_y, v_z)^T$ of the satellite from the image movement of the rim of the earth $\left(\frac{dx}{dt}, \frac{dy}{dt}\right)$:

$$\frac{dx}{dt} = f / Z * \left(-v + x v_z\right) + C_x$$

$$\frac{dy}{dt} = f / Z * \left(v_y + y v_z\right) + C_y \qquad (2)$$

Z denotes the distance to the earth's horizon which in this case is constant. C_x, C_y are constants which depend on the known rates of rotation as follows:

$$C_x = \frac{xy}{f}\omega_x + \left(-f - \frac{x^2}{f}\right)\omega_y + y\omega_z$$

$$C_y = \left(f + \frac{y^2}{f}\right)\omega_x - \frac{xy}{f}\omega_y - x\omega_z \qquad (3)$$

Again, two points $(x, y)^T$ of the rim of the earth are sufficient to estimate the orbit components. If Z is unknown, the speeds can only be determined up to a constant factor. If the rim of the earth is only imaged

as a linear or quasi-linear element, then (2) only contains a measurement for the unknown quantities v_x, v_y, v_z.

Thus simultaneous orbit determination and attitude determination can thus for example take place via the following steps:

a) Determining the star attitude in the focal plane by means of a method with subpixel accuracy, such as e.g. centroiding;

b) Determining the rates of rotation by tracking the centroid of a surface of the stars and inverting the image equations;

c) Determining the rim of the earth by model-supported image-processing methods with subpixel accuracy;

d) Estimating the centre of the earth from the image of the rim of the earth, as far as possible; and

e) Model-based tracking of the rim of the earth so as to obtain additional degrees of freedom.

CLAIMS

1. A combined earth-star sensor system for three-axis attitude determination of satellites in space, characterised in that the combined earth-star sensor system (1) comprises separate apertures with different directions of observation and common image pickup devices (4) for the earth sensor and the star sensor.

2. The sensor system according to claim 1, characterised in that the earth-star sensor system (1) comprises a common optical arrangement (2) for earth observation and star observation, and a deflection mirror (3) for deviation of the laterally entering light from the earth, to the common optical arrangement (2).

3. The sensor system according to claim 1, characterised in that the earth-star sensor system (1) comprises an optical arrangement (9) for star observation, an optical arrangement (10) for earth observation and a semitranslucent beam splitter (8) for deviating the laterally entering light from the earth and transferring the starlight which enters in longitudinal direction, to the image pickup devices (4).

4. The sensor system according to one of claims 1 to 3, characterised in that the aperture for the light from the earth is considerably smaller than the aperture for the starlight.

5. The sensor system according to one of claims 1 to 4, characterised in that the evaluation system of the sensor system by means of a star catalogue or similar prior knowledge disregards those areas in

the image where the image of the rim of the earth and images of stars are superimposed, thus eliminating influences of interference concerning the accuracy of determining the rim of the earth in the image.

6. A method for simultaneous orbit determination and attitude determination of a space vehicle, characterised by the steps:

- Simultaneous imaging of stars and the rim of the earth in one focal plane of a sensor system;

  Determining the star attitude in the focal plane;

- Determining the rim of the earth by image processing;

- Determining the rates of rotation of the sensor system from the movement of the star image in the focal plane; and

- Calculating the orbit and/or attitude of a space vehicle carrying the sensor system.

7. The method according to claim 6, further characterised by model-based tracking of the rim of the earth.

8. The method according to claim 6 or 7, characterised in that a long-wave fraction of the radiation is filtered out and used for determining the rim of the earth.

9. The method according to one of claims 6 to 8, characterised in that the rim of the earth is determinod by fitting earth models.

10. Tho method according to one of claims 6 to 9, characterised in that exposure time or integration time is adapted in turn to the difference in brightness of the stars and of the earth.